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# Neutrino masses through a type II seesaw mechanism at TeV scale

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## Abstract

In this work we show that we can generate neutrino masses through the type-II see-saw mechanism working at TeV scale in the context of a 331 model.

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The explanation of the smallness of the neutrino masses and the profile of its mixing as required by recent experiments has being taken as a great puzzle in particle physics. This is so true that in the past three years a great amount of papers have been devoted to its solution. Despite the volume of papers, we still dispose of few basic ideas to explore the puzzle [1]. In the context of the electroweak $SU(2)_L \otimes U(1)_Y$ model a very attractive idea is centered on a very heavy Higgs-triplet $\Delta$ [2].

With this scalar triplet, $\Delta$, it is possible to implement the spontaneously breakdown of the total lepton number and generate neutrino majorana masses [3]. Its main consequence was the existence of a Goldstone-boson named the majoron-triplet. This Goldstone boson has many implications in collider, astro-particle, and cosmo-particle physics, so that the model received great attention until it was ruled out by LEP data [4].

In order to save the idea a term that violates explicitly the lepton number,

$$M' \phi^T \Delta^\dagger \phi, \tag{1}$$

was considered in the scalar potential. If we decouple the Higgs-triplet of the electro-weak scale, i.e., taking it as a very heavy triplet, the majoron hence gains a mass, getting safe from LEP data, we get a tiny value for the vacuum expectation value (VEV) of the $\Delta$ field. To see that, consider below the potential with the term that violates explicitly the lepton number:

$$\begin{aligned} V(\phi, \Delta) = -M^2 \Delta^\dagger \Delta - \mu^2 \phi^\dagger \phi + \lambda_\phi (\phi^\dagger \phi)^2 + \lambda_\Delta (\Delta^\dagger \Delta)^2 \\ \lambda_{\Delta\phi} \Delta^\dagger \Delta \phi^\dagger \phi + M' \phi^T \Delta^\dagger \phi \end{aligned} \tag{2}$$

From the condition that the neutral component of the Higgs-triplet develop a VEV we find the following relation among the vacua of the model:

$$v_\Delta \sim \frac{v_\phi^2}{M} \ll v_\phi. \tag{3}$$

To find the relation above the condition $M \sim M' \gg v_\phi$ was used. Choosing $v_\phi = 10^2$ GeV and $M = 10^{14}$ GeV, we get $v_\Delta = 0.1$ eV. This mechanism was labeled type II seesaw and when used in conjunction with some additional global symmetries, in order to generate the wanted entries in the neutrino mass matrices, it is the main ingredient of various interesting extensions of the standard model [5].

In Refs. [6] it was shown that the required Higgs-triplet appears in the minimal version of the 331 models [7] embedded in an scalar sextet $S$. In fact, the sextet $S$ can be decomposed under $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ as follows: $S \longrightarrow \Delta_{(\mathbf{1},\mathbf{3},-2)} + \Phi_{3_{(\mathbf{1},\mathbf{2},1)}} + H^{++}_{2_{(\mathbf{1},\mathbf{1},4)}}$, when the 331 symmetry breaks to the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y(321)$ symmetry. As in the triplet majoron scheme, when the neutral component of the triplet $\Delta$ develops a VEV, we have the spontaneous breaking of the total lepton number, and therefore, the model develops a majoron-triplet too [6]. However, in the present model the majoron-triplet can be safe under LEP data [8]. A natural step further in the development of the 331 model is to add to its scalar potential a term that is equivalent to that one that gave rise the type II seesaw mechanism in the standard electroweak model with the triplet $\Delta$.

The scalar sector of the minimal 331 model is composed by three triplet and a sextet of scalars.

$$\eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^+ \end{pmatrix}, \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{++} \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^- \\ \chi^{--} \\ \chi^0 \end{pmatrix}, \quad S = \begin{pmatrix} \sigma_1^0 & \frac{h_2^-}{\sqrt{2}} & \frac{h_1^+}{\sqrt{2}} \\ \frac{h_2^-}{\sqrt{2}} & H_1^{--} & \frac{\sigma_2^0}{\sqrt{2}} \\ \frac{h_1^+}{\sqrt{2}} & \frac{\sigma_2^0}{\sqrt{2}} & H_2^{++} \end{pmatrix}. \tag{4}$$

After the breaking of the 331 symmetry to the standard 321 symmetry, the sextet above will decompose under $3-2-1$ in the following triplet, doublet and singlet of scalars:

$$\Delta = \begin{pmatrix} \sigma_1 & \frac{h_2^-}{\sqrt{2}} \\ \frac{h_2^-}{\sqrt{2}} & H_1^{--} \end{pmatrix}, \quad \Phi_3 = \frac{1}{\sqrt{2}} \begin{pmatrix} h_1^+ \\ \sigma_2 \end{pmatrix}, \quad H_2^{++}. \tag{5}$$

With all those scalar multiplets in (4) we have the following potential which is invariant under the 331 gauge symmetry [6,9]:

$$\begin{aligned} V(\eta,\rho,\chi,S) = {} & \mu_\eta^2 \eta^\dagger \eta + \mu_\rho^2 \rho^\dagger \rho + \mu_\chi^2 \chi^\dagger \chi + \mu_S^2 Tr(S^\dagger S) + \lambda_1 (\eta^\dagger \eta)^2 + \lambda_2 (\rho^\dagger \rho)^2 + \lambda_3 (\chi^\dagger \chi)^2 \\ & + (\eta^\dagger \eta)\left(\lambda_4 (\rho^\dagger \rho) + \lambda_5 (\chi^\dagger \chi)\right) + \lambda_6 (\rho^\dagger \rho)(\chi^\dagger \chi) + \lambda_7 (\rho^\dagger \eta)(\eta^\dagger \rho) + \lambda_8 (\chi^\dagger \eta)(\eta^\dagger \chi) \end{aligned}$$

$$+\lambda_9(\rho^\dagger\chi)(\chi^\dagger\rho)+\lambda_{10}Tr(S^\dagger S)^2+\lambda_{11}\left(Tr(S^\dagger S)\right)^2+\left(\lambda_{12}(\eta^\dagger\eta)+\lambda_{13}(\rho^\dagger\rho)\right)Tr(S^\dagger S)$$
$$+\lambda_{14}(\chi^\dagger\chi)Tr(S^\dagger S)+\left(\lambda_{15}\epsilon^{ijk}(\chi^\dagger S)_i\chi_j\eta_k+h.c\right)+\left(\lambda_{16}\epsilon^{ijk}(\rho^\dagger S)_i\rho_j\eta_k+h.c\right)$$
$$+\left(\lambda_{17}\epsilon^{ijk}\epsilon^{lmn}\eta_n\eta_k S_{li}S_{mj}+h.c\right)+\lambda_{18}\chi^\dagger SS^\dagger\chi+\lambda_{19}\eta^\dagger SS^\dagger\eta+\lambda_{20}\rho^\dagger SS^\dagger\rho. \quad (6)$$

In this work, for the sake of simplicity, we impose to the scalar potential the symmetry $\chi\rightarrow-\chi$ in order to avoid other trilinear terms besides the one that will generate the seesaw mechanism.

The scalar potential above is not the total potential permitted by the 331 gauge symmetry. It permits more four terms which violate explicitly the lepton number, but for what concern us here we just will consider one of them:

$$M'\eta^T S^\dagger\eta, \quad (7)$$

since it is only important to the minimum of the potential, and also because it contains, after the decomposition (5), the term (1) which generated the seesaw mechanism in the Gelmini-Roncadelli scheme.

Adding the term (7) to the potential in (6), we find the following minimum condition to that the scalar field $\sigma_1^0$ develops a vacuum:

$$v_{\sigma_1}\left(\mu_S^2+\lambda_{10}v_{\sigma_2}^2+\frac{\lambda_{12}}{2}v_\eta^2+\frac{\lambda_{13}}{2}v_\rho^2+\frac{\lambda_{14}}{2}v_\chi^2+\frac{\lambda_{19}}{2}v_\eta^2\right)+M'v_\eta^2+\frac{\lambda_{11}}{2}v_{\sigma_1}^3+\lambda_{10}v_{\sigma_1}^3=0. \quad (8)$$

Considering that $v_\chi$ is dominant over the other vacua, which is a plausible consideration since this VEV is the only responsible by the breaking of the 331 symmetry, and taking also natural values for the parameters $\lambda$'s, i.e., $\lambda's\sim\mathcal{O}(1)$, we find the following expression to the vacuum of the field $\sigma_1^0$

$$v_{\sigma_1}\sim M'\frac{v_\eta^2}{v_\chi^2}. \quad (9)$$

From the minimum condition to the scalar fields $\sigma_2^0$ and $\eta^0$ develop a VEV we have more two constraints over the vacua of the model:

$$v_\eta\left(\mu_\eta^2+\frac{\lambda_4}{2}v_\rho^2+\frac{\lambda_5}{2}v_\chi^2+\lambda_{12}(\frac{v_{\sigma_1}^2}{2}+\frac{v_{\sigma_2}^2}{2})\;-\lambda_{17}v_{\sigma_2}^2+\frac{\lambda_{19}}{2}v_{\sigma_1}^2\right)$$
$$+\frac{v_{\sigma_2}}{2\sqrt{2}}(\lambda_{15}v_\chi^2-\lambda_{16}^2v_\rho^2)+\lambda_1 v_\eta^3=0,$$
$$v_{\sigma_2}\left(\mu_S^2+\lambda_{10}v_{\sigma_1}^2+\frac{\lambda_{12}}{2}v_\eta^2+\frac{\lambda_{13}}{2}v_\rho^2+\frac{\lambda_{14}}{2}v_\chi^2-\lambda_{17}v_\eta^2+\frac{\lambda_{18}}{4}v_\chi^2+\frac{\lambda_{20}}{4}v_\rho^2\right)$$
$$+\frac{\lambda_{15}}{2\sqrt{2}}v_\eta v_\chi^2-\frac{\lambda_{16}}{2\sqrt{2}}v_\eta v_\rho^2+\frac{\lambda_{11}}{2}v_{\sigma_2}^3+\lambda_{10}v_{\sigma_2}^3=0, \tag{10}$$

which give, by using the same approximations used to obtain (9), the following relation among $v_{\sigma_2}$ and $v_\eta$:

$$v_\eta\sim v_{\sigma_2}. \tag{11}$$

The result above is interesting because, together with Eq. (9), provides a relation among the VEVs of the two neutral components of the sextet:

$$v_{\sigma_1}\sim M'\frac{v_{\sigma_2}^2}{v_\chi^2}. \tag{12}$$

As the two vacua $v_{\sigma_1}$ and $v_{\sigma_2}$ have the same origin, the sextet, we could expect that they had the same order of magnitude. But we know that $v_{\sigma_1}$ should be of the order of eV to explain the neutrino mass. However if we take $v_{\sigma_2}$ of the order of eV we can not explain the charged lepton masses. As the field $\sigma_2^0$ only contributes to the charged lepton masses it should develop a VEV around the scale of GeV. We can wonder if the scalar potential, with the VEVs above and the required $\lambda$s, is bounded from below. Although we have not done a detailed analysis we note that this condition can be assured by the $\lambda_3\chi^\dagger\chi$ term in (6) with $\lambda_3>0$.

Next we are going to discuss the best value to the set of parameters $M'$ , $v_{\sigma_2}$ and $v_\chi$ which could better explain the neutrino and charged lepton masses. In the minimal 331 model the neutrinos and the leptons obtain their masses from the following Yukawa interactions [10]

$$\mathcal{L}_l^Y=\frac{1}{2}\overline{(\Psi_{aL})^c}G_{ab}\Psi_{b_L}S+\epsilon^{ijk}\overline{(\Psi_{iaL})^c}F_{ab}\Psi_{jbL}\eta_k^*. \tag{13}$$

with $\Psi_{aL}=(\nu_a\, l_a\, l^c)_L^T$ $a=e,\mu,\tau$; and we have omitted $SU(3)$ indices. After the scalar fields $\sigma_1^0$, $\sigma_2^0$ and $\eta^0$ develop their VEVs the interactions above generate the following mass terms to the neutrinos and charged leptons

$$\mathcal{L}_l^Y = \frac{v_{\sigma_1}}{2\sqrt{2}}\overline{(\nu_{a_L})^c}G_{ab}\,\nu_{b_L} + \bar{l}_{a_L}\left(\frac{v_{\sigma_2}}{4}G_{ab} + \frac{v_\eta}{\sqrt{2}}F_{ab}\right)l_{b_R}, \tag{14}$$

with the matrix $F_{ab}$ being anti-symmetric [10].

Using the relations (11) and (12) in (14), we find the following expressions to the masses of the neutrinos and charged leptons

$$m^\nu_{ab} = \frac{G_{ab}M' v^2_{\sigma_2}}{2\sqrt{2}v^2_\chi}, \quad m^l_{ab} = \left(\frac{G_{ab}}{4} + \frac{F_{ab}}{\sqrt{2}}\right)v_{\sigma_2}. \tag{15}$$

The best choice for the set of parameters $M'$, $v_{\sigma_2}$ and $v_\chi$, in order to explain the smallness of the neutrinos masses and also the charged lepton masses, is : $M' = v_{\sigma_2} = 1$ GeV and $v_\chi = 10$ TeV. With this values we have the following mass matrices to both sectors:

$$m_\nu = 3\begin{pmatrix} G_{11} & G_{12} & G_{13} \\ G_{12} & G_{22} & G_{23} \\ G_{13} & G_{23} & G_{33} \end{pmatrix} eV,$$

$$m_l = \begin{pmatrix} \frac{G_{11}}{4} & \frac{G_{12}}{4} + \frac{F_{12}}{\sqrt{2}} & \frac{G_{13}}{4} + \frac{F_{13}}{\sqrt{2}} \\ \frac{G_{21}}{4} - \frac{F_{12}}{\sqrt{2}} & \frac{G_{22}}{4} & \frac{G_{23}}{4} + \frac{F_{23}}{\sqrt{2}} \\ \frac{G_{31}}{4} - \frac{F_{13}}{\sqrt{2}} & \frac{G_{23}}{4} - \frac{F_{23}}{\sqrt{2}} & G_{33} \end{pmatrix} GeV. \tag{16}$$

The texture of the neutrino mass matrices is a question of try to put extra global symmetries in order to generate the wanted entries [11]. That is not the intention in this work. Nevertheless, we can conclude from the matrices above that the minimal 331 model perhaps prefers a texture where the charged lepton matrix is not diagonal, unless we find some symmetry to justify the fine-tuning $G_{ab} = -G_{ba} = \frac{4}{\sqrt{2}}F_{ab},\ a \neq b$.

Now let us briefly analyze the type II seesaw with a very heavy sextet, i.e., considering $\mu_S \sim M' \sim 10^{14}$ GeV, as in the traditional type II seesaw scheme. In this scenario the minimum condition in (8) give us the following expression to the vacuum of the field $\sigma^0_1$:

$$v_{\sigma_1} \sim \frac{v^2_\eta}{\mu_S}, \tag{17}$$

Choosing $\mu_S = 10^{14}$ GeV and $v_\eta = 10^2$ GeV we have $v_{\sigma_1} \sim 0.1$ eV, which is completely identical to the traditional case. However, from the minimum condition to the field $\sigma^0_2$ in (11) we find the following expression to its VEV

$$v_{\sigma_2} \sim \frac{v_\chi v_\eta^2}{\mu_S^2}. \tag{18}$$

Choosing $v_\chi = 10$ TeV and $v_\eta = 10^2$ GeV we have $v_{\sigma_2} = 10^{-20}$ GeV. With this value to $v_{\sigma_2}$ only $\eta$ is responsible by the charged lepton masses. However we already know that $\eta$ alone is not sufficient the generate the correct charged lepton masses [10]. Then to have a type II seesaw mechanism with a very heavy sextet we should extent the model in order to generate the correct charged lepton masses. In this case a minimal extension, for example, is the one where two fermions transforming like singlet under the 331 symmetry, $E_L \sim (\mathbf{1}, \mathbf{1}, 1)$ and $E_R \sim (\mathbf{1}, \mathbf{1}, 1)$, are added to the model, as suggested by Duong and Ma [12] and developed in Ref. [13].

In conclusion, we showed that we can implement a type II seesaw mechanism for generating neutrino masses working at TeV scale in the context of the minimal version of the 331. After this work was almost concluded we found that a similar idea was pointed out in Ref. [14]. This is a very interesting result because only few models are able to explain the neutrino puzzle at the tree level without resort to very high scale of energy.

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